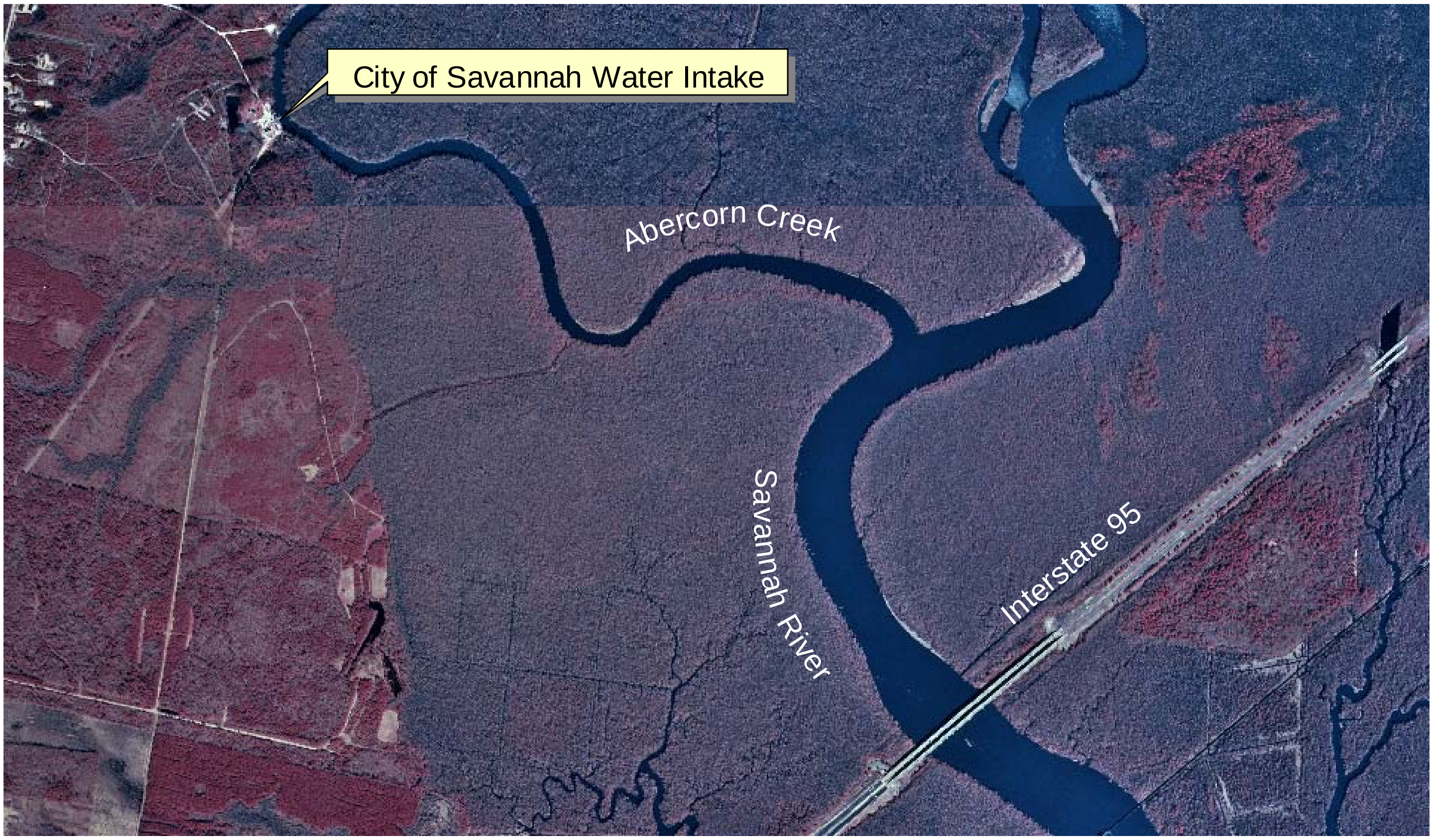
Savannah Harbor Expansion Project - Chloride Data Analysis and Model Development



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1.0 Introduction

Tetra Tech, Inc. (Tetra Tech) was contracted by the United States Army Corps of Engineers (USACE) to perform a data analysis of chloride concentrations in Abercorn Creek upstream of the Interstate 95 (I-95) Bridge on the Savannah River. The purpose of the chloride data analysis was to determine a prediction of chloride concentrations (or chloride mode) on Abercorn Creek in response to downstream harbor modifications. The City of Savannah (City) owns and operates an Industrial and Domestic drinking water supply intake located on Abercorn Creek approximately two miles from the confluence with the Savannah River. The City collects samples at the water treatment plant everyday to monitor different chemical constituents in the influent.

Chloride is a major concern for the City as elevated concentrations require additional treatment, which can significantly impact existing resources. It is noted here that a chloride concentration of 12 mg/L was used throughout this document only as an assumed benchmark specifically for the purposes of this analysis. The use of this benchmark does not constitute, nor is derived from any legal standard or criterion to be achieved by the City of Savannah. Further, this benchmark does not impact the analysis of the final results and is not used as an indicator to assess the degree by which the model's output may or may not be related to the chloride measurements observed by the City. The benchmark acts only as a reference value for the purposes of this report.

The data analysis and model presented in this report describe the sources of chloride in the Savannah River and the prediction of chloride levels at the water intake based on river flows, salinity intrusion from the harbor, and other direct and indirect sources.

2.0 Objectives

The overall goal of this report is to provide an analysis of the potential for a proposed harbor modifications (i.e., deepening of the navigation channel) to cause an increase in the chloride concentrations at the City of Savannah's freshwater intake on Abercorn Creek. In addition to defining the data used in the analysis, this study will provide the following:

- Provide a statistical correlation between chloride levels at the City's intake, chloride levels at a nearby downstream station, and upstream flows.
- Illustrate the likelihood of increased chloride levels at the City's intake, based on previous deepening of the Savannah Harbor.
- Identify potential point and non-point sources of chlorides within the watershed.
- Chloride model to predict changes in concentrations at the City's intake.

3.0 Study Area Description

The Savannah River basin includes portions of North Carolina, South Carolina, and Georgia and flows through the Blue Ridge Mountain, Piedmont, and Coastal Plain provinces. The Savannah River forms the boundary between South Carolina and Georgia and begins at Hartwell Reservoir by the confluence of the Seneca and Tugaloo Rivers. From this point, it flows southeast to the port city of Savannah, Georgia where it empties into the Atlantic Ocean (River Basin Center).

The city of Savannah owns and operates the 75 Million Gallons per Day (MGD) Industrial and Domestic (I&D) Water Treatment Plant. The plant was constructed in 1947 as a 35 MGD conventional surface water treatment plant. The treatment plant and its associated processes have been improved and/or upgraded over the years to its current 75 MGD maximum capacity.

The raw water source for this facility is Abercorn Creek, a tributary of the Savannah River. Due to the proximity of Savannah to the coast, the rise and fall of daily tides causes the physical and chemical characteristics of the source water to change continuously. This constant change adds to the complexity of the treatment process and requires the highest degree of vigilance by the operations staff. Figures 3-1 through 3-3 provide a location map of the watershed, location of the water intake on Abercorn Creek, and the United States Geological Survey (USGS) data collection stations.

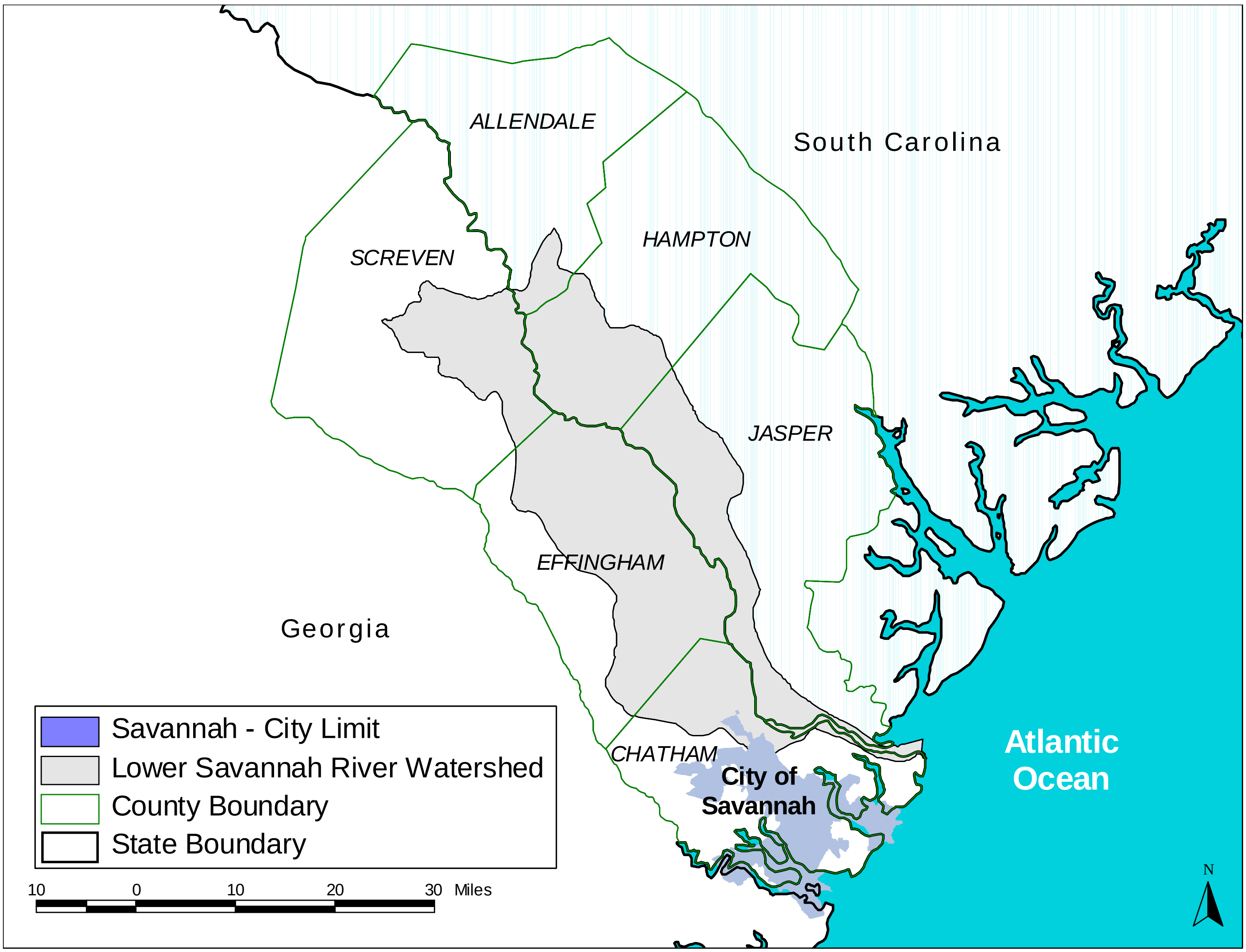

Figure 3-1 Location Map of the Savannah River Watershed

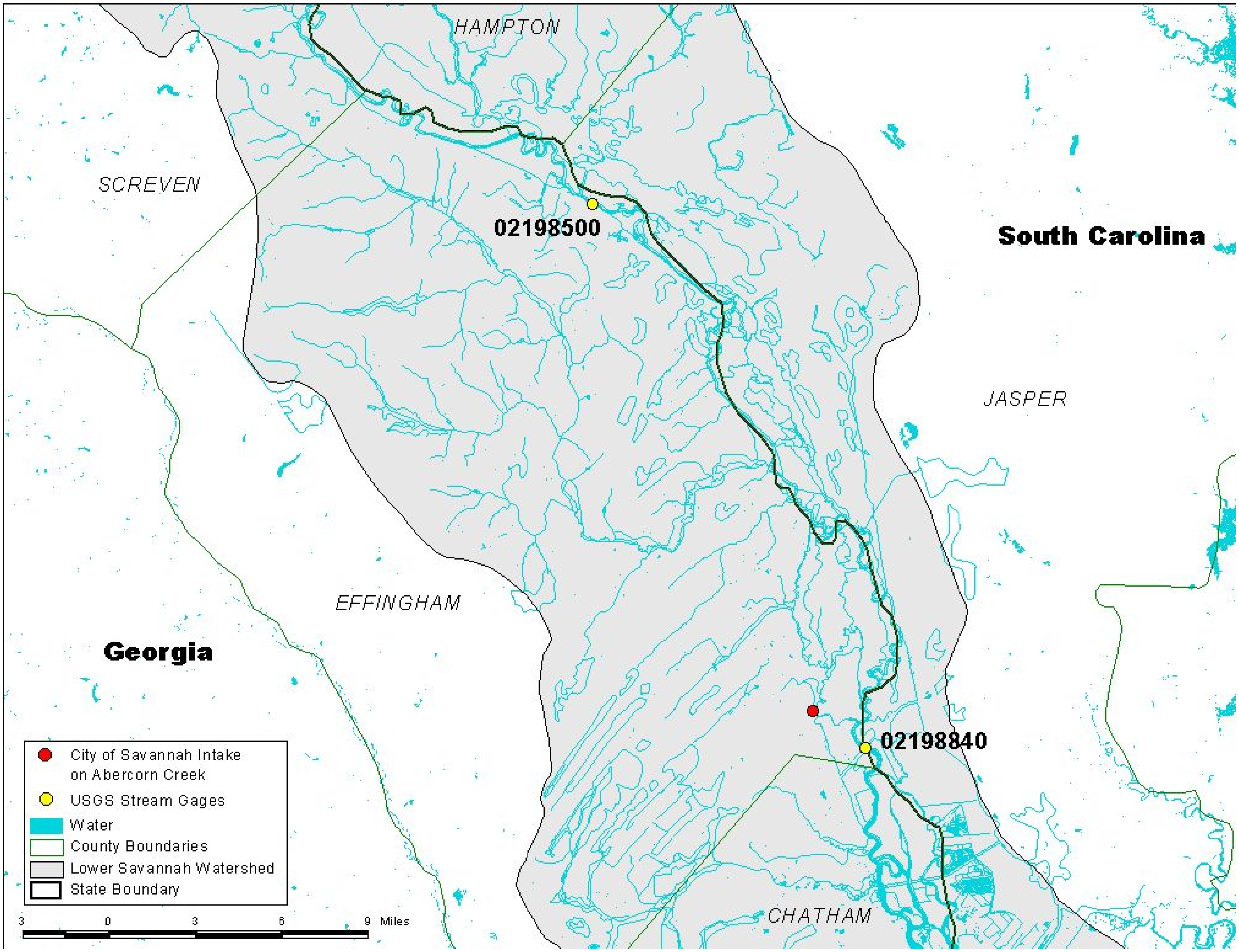

Figure 3-2 City of Savannah I&D WTP Intake and Nearby USGS Monitoring Stations

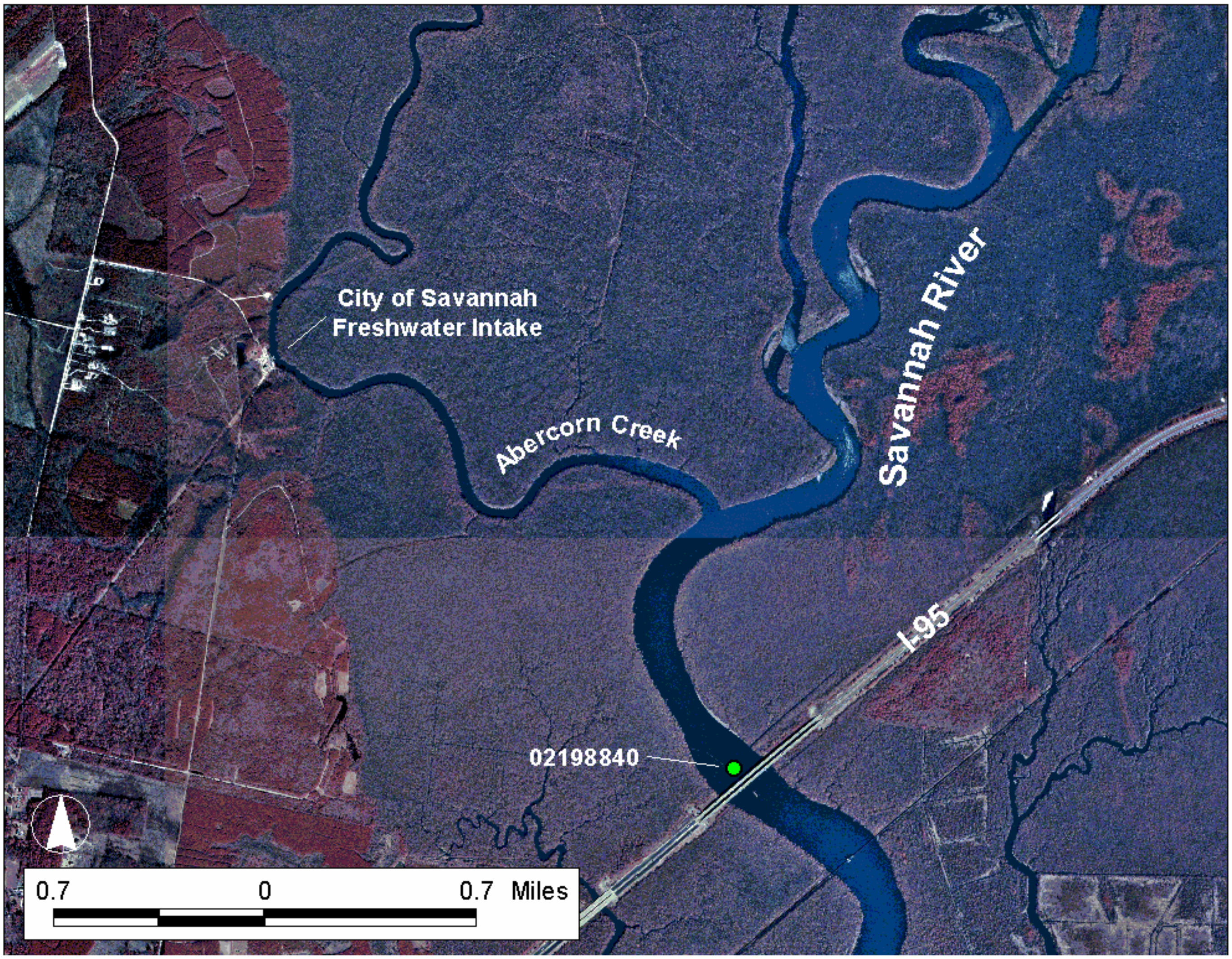

Figure 3-3 City of Savannah Freshwater Intake and the USGS Station at the I-95 Bridge (02198840)

4.0 Available Data

The sources and types of data utilized in this analysis are indicated in Table 4-1.

Table 4-1 Sources and Types of Data Employed

Agency	Station ID	Station Description	Data Employed	Period of Record
City of Savannah	---	Abercorn Creek Freshwater Intake (City)	Chloride (mg/L)	1/1988 – 12/2003
USGS	02198500	Savannah River Near Clyo, Georgia (Clyo)	Chloride (mg/L), Flow (cfs)	1/1988 – 9/2003
USGS	02198840	Savannah River Near Port Wentworth, Georgia (I-95 Bridge)	Specific Conductivity (μS/cm)	1/1988 – 12/2003
GPA	14, 18, 19	Savannah River and Abercorn Creek	Conductivity (μS/cm)	Summer 1999
USGS	several	Upper Savannah River watershed	Chloride (mg/L)	1956 - 2003

The City of Savannah obtains grab samples at the water plant rather than at the end of the intake pipe on Abercorn Creek. These samples are typically taken daily at approximately 7:30 AM during the weekdays and are measured for chloride concentrations, along with many other parameters, at the water treatment facility.

The two USGS stations used in this analysis provide upstream daily flow in the Savannah River near Clyo, Georgia (02198500), and downstream specific conductivity where I-95 crosses the Savannah River (02198840). These stations are 50 and 25 miles from the mouth of the river, respectively. The conductivity values from 02198840 were converted to chloride values, in mg/L, to allow comparison with data obtained at the City's intake. This was accomplished using a well-established algorithm developed to define the relationship of specific conductance to the chemical composition in seawater and dilutions of seawater, as in estuaries (Miller, 1988).

There can be potential interferences with the conversion of specific conductance to chloride, such as dissolved organic solids from local wetland and swamp areas. The relationships between flow, chloride, and conductivity were developed assuming that the interference is small to negligible over a longterm period. Therefore, for this analysis, it is assumed to not have a significant factor on specific conductance.

Chloride is one of the major inorganic anions, or negative ions, in saltwater and freshwater. It originates from the dissociation of salts, such as sodium chloride or calcium chloride, in water. Chlorides are binary compounds of chlorine. Chlorine chemically combines with a metal to form chloride. Salinity is the total of all non-carbonate salts dissolved in water. This is comprised mostly by chloride (55%) and sodium (31%) ions with sulfate, magnesium, calcium, potassium, and bicarbonate ions comprising the remaining 14%.

Once converted to similar units, the chloride data from the City's intake site, calculated chloride data from the I-95 bridge station, and the corresponding daily flow data from the USGS Clyo station were graphed (Figure 4-1) to provide a cursory relation between these three variables. Figure 4-1 also illustrates periods of similar trends (circled on the graph) between chloride values at the intake, and those taken at the I-95 Bridge (USGS 02198840). The chloride benchmark of 12 mg/L used specifically for this analysis is shown on all of the plots for reference.

As observed in Figure 4-1, increased flows tend to result in lower chloride levels at both the City and I-95 stations. This apparent relationship is most obvious in periods of drastically increased flows, such as in 1993, 1998, and 2003. Representative years for 1990, 1993, 1996, 2000, and 2003 are plotted in Figures 4-2 through 4-6.

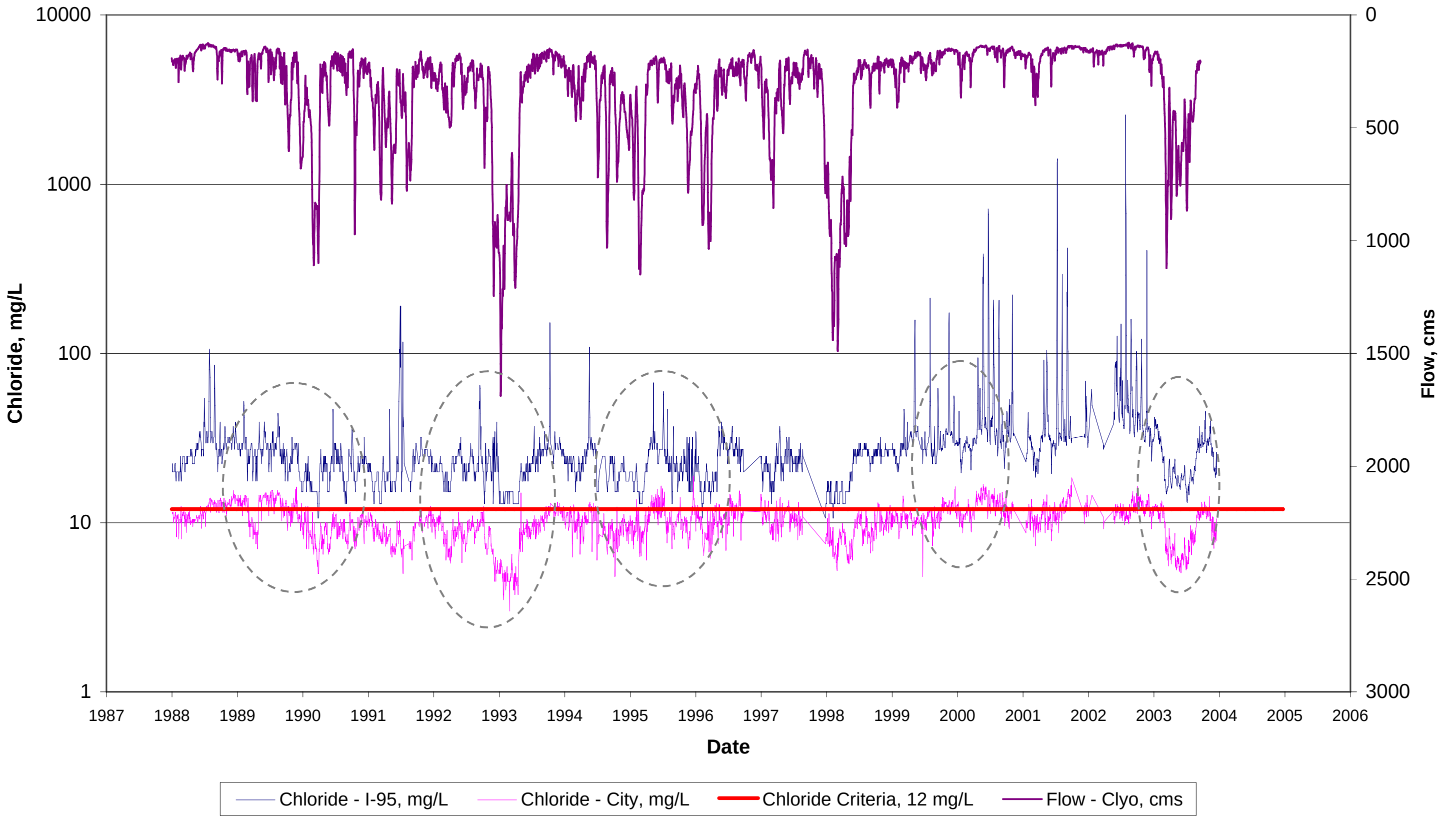

Figure 4-1 Chloride Values and Corresponding Flow Measurements

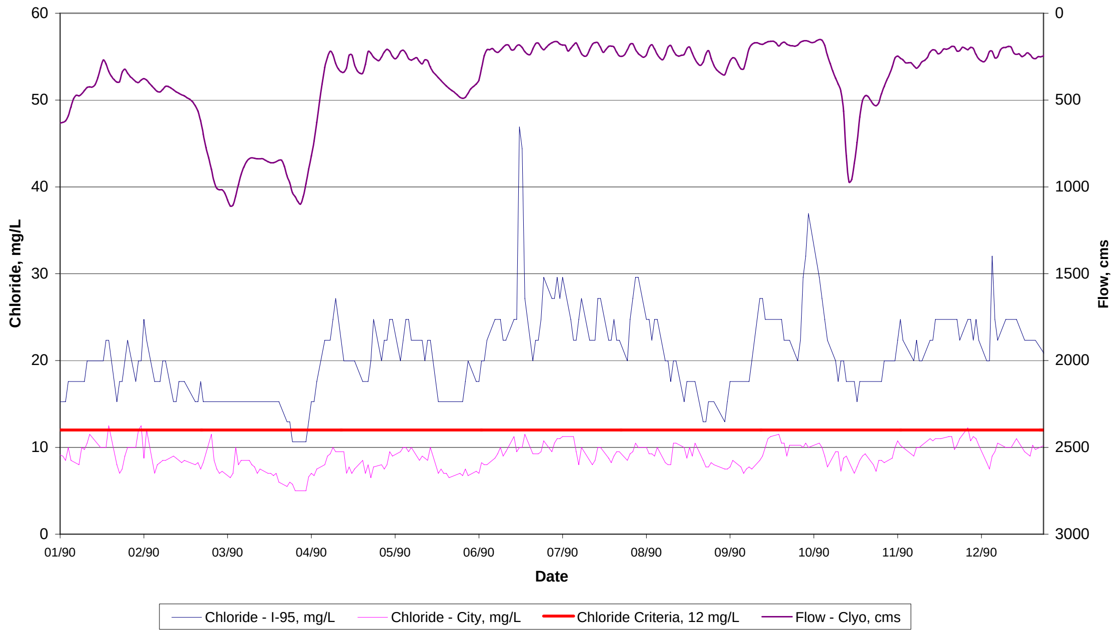

Figure 4-2 Chloride Values and Corresponding Flow Measurements for 1990

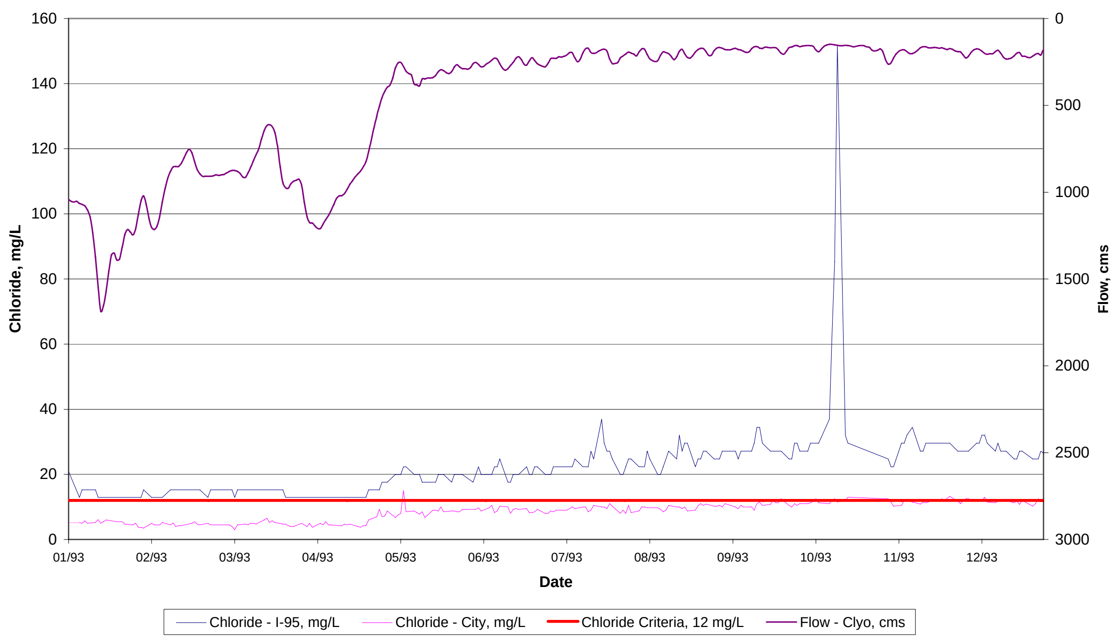

Figure 4-3 Chloride Values and Corresponding Flow Measurements for 1993

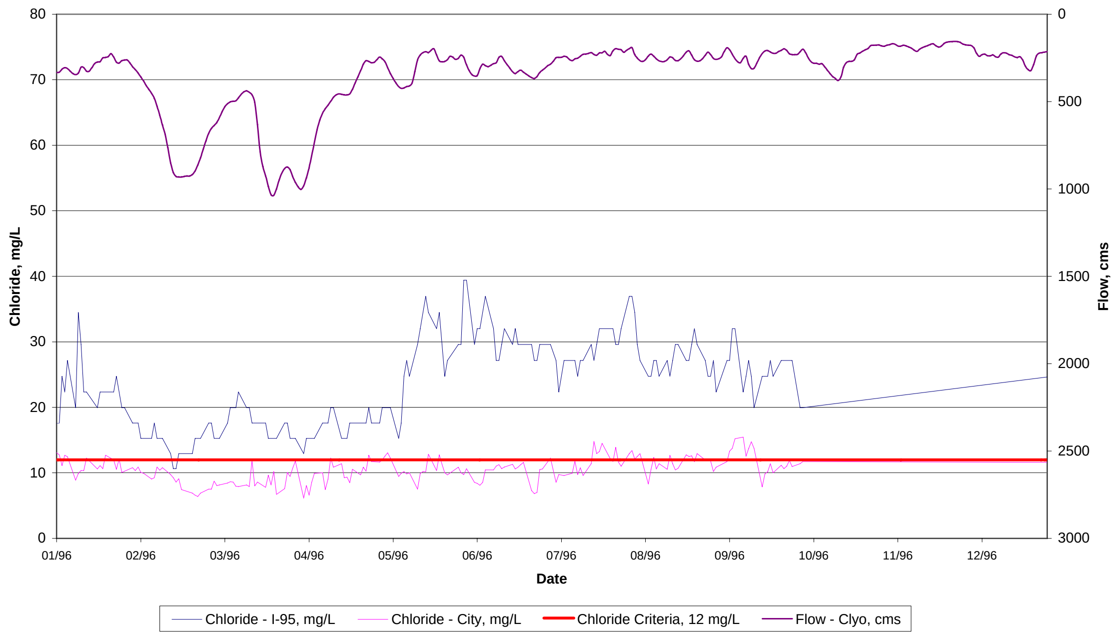

Figure 4-4 Chloride Values and Corresponding Flow Measurements for 1996

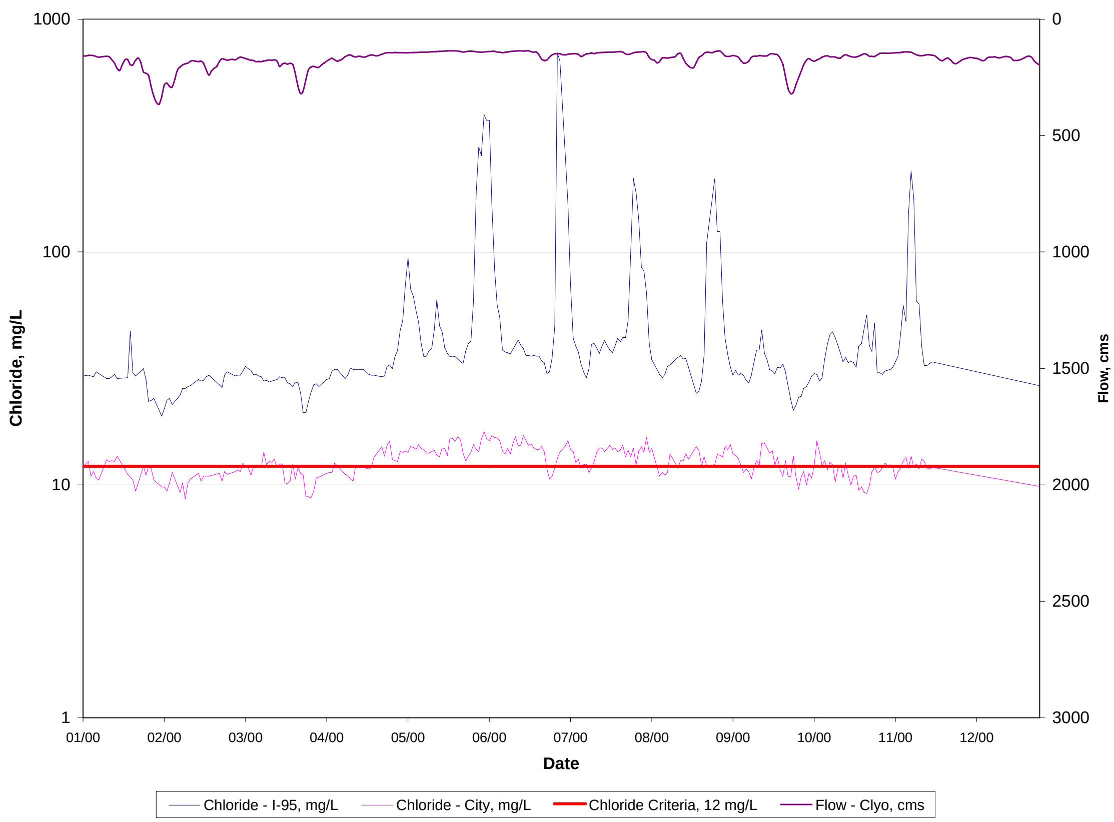

Figure 4-5 Chloride Values and Corresponding Flow Measurements for 2000

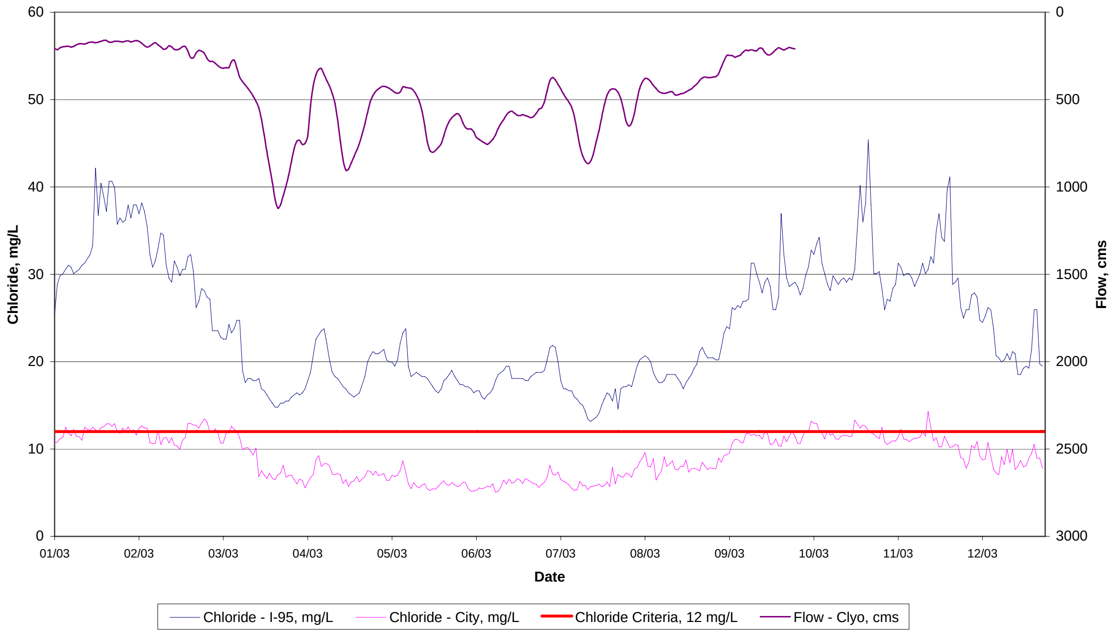

Figure 4-6 Chloride Values and Corresponding Flow Measurements for 2003

It is quite clear from the preceding graphs that at higher flows, chloride values at both stations are depressed, indicating that some saltwater intrusion is being suppressed by the increased upstream freshwater discharge, though a low-level chloride signal still remains.

At relatively lower flows, the chloride response is expectedly different. The ability for saltwater intrusion to have a greater impact on the chloride concentrations at both stations is anticipated, as upstream freshwater is not available to aid in the flushing process. Interestingly though, Figure 4-7 shows a relatively low flow period where chloride concentrations at the I-95 Bridge station exhibit tidally influenced, approximately 30-day chloride spikes, which immediately disappear with increased flow. Though lower flows do seem to correspond with slightly increased City chloride concentrations, the 30-day chloride spikes are not at all apparent there. This may imply that the impact of low flows and greater saltwater intrusion affect the I-95 station, located on the mainstem of the Savannah River, but do not have as significant an effect on chloride concentrations at a station located on Abercorn Creek, 2 miles upstream of the I-95 Bridge.

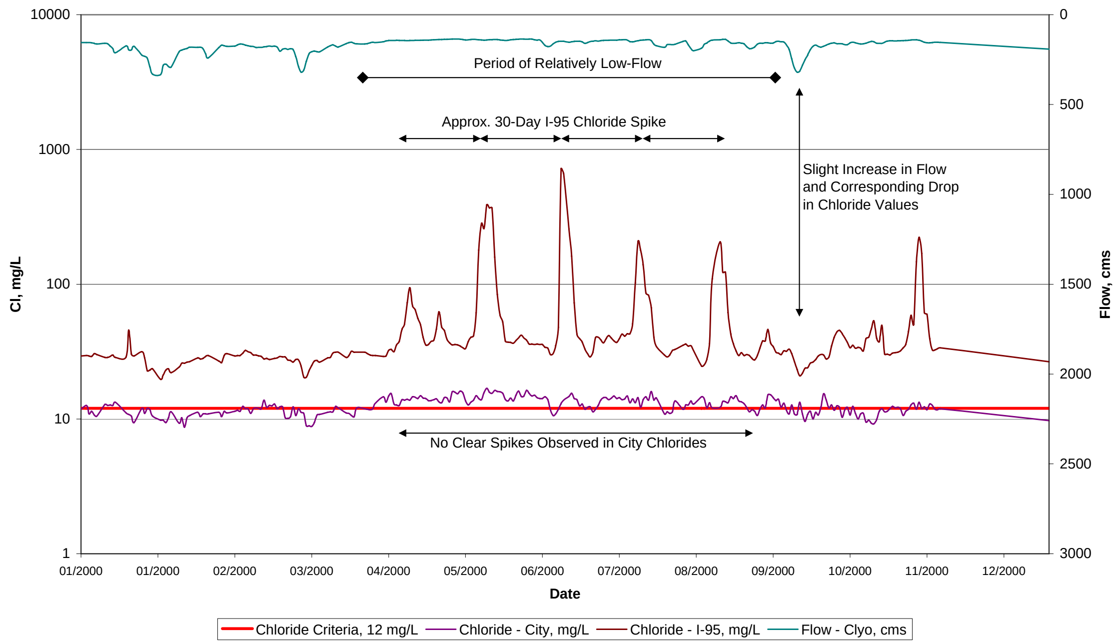

Figure 4-7 Illustration of the Effect of Flow and Tides on Chloride Values in the System

5.0 Data Analysis

5.1 Linear Regression

Specific conductance data were obtained from USGS for the I-95 Bridge location (02198840). Before proceeding further in this analysis, it was important to first establish the relation, if one exists, between the two chloride sampling stations and the corresponding daily flow measurements from the Clyo USGS station. This relation may be determined statistically in terms of a linear regression between these three variables, which was conducted for two cases; between the two chloride stations, between each chloride station, and corresponding flow measurements.

The correlation of chloride values sampled at the intake against flow values from the USGS station at Clyo, and then with chloride values from the I-95 Bridge station and flow are presented in Table 5-1 as R-squared values for the period of record and annually. The results indicate that 1998 and 2003 were the strongest years of correlation overall as evident with higher flow periods.

Table 5-1 Linear Regression of City Chlorides and I-95 Chlorides against Flow Values from Clyo Gauge (USGS 02198500)

	City CL / Flow at Clyo		I-95 CL / Flow at Clyo	
Year	**r**	**R^2**	**R**	**R^2**
ALL	-0.670	0.449	-0.148	0.022
1988	-0.422	0.178	-0.502	0.252
1989	-0.481	0.231	-0.652	0.425
1990	-0.549	0.302	-0.657	0.432
1991	-0.670	0.449	-0.213	0.045
1992	-0.733	0.537	-0.055	0.003
1993	-0.862	0.743	-0.517	0.267
1994	-0.464	0.215	-0.483	0.233
1995	-0.578	0.335	-0.577	0.332
1996	-0.572	0.327	-0.702	0.493
1997	-0.471	0.222	-0.680	0.462
1998	-0.646	0.417	-0.923	0.852
1999	-0.379	0.144	-0.285	0.081
2000	-0.503	0.253	-0.213	0.046
2001	-0.548	0.300	-0.151	0.023
2002	-0.166	0.027	-0.122	0.015
2003	-0.825	0.680	-0.831	0.691

The correlation between chloride values at the intake and those from the I-95 Bridge station are presented in Table 5-2 as R-squared values for the period of record and annually. The results indicate that 1998 and 2003 seem to have the strongest correlations, again high flow years.

Table 5-2 Yearly Linear Regression of City Chloride Samples and Chloride Values Generated with data from the I-95 Station (USGS 02198840)

	City CL / I-95 CL	
Year	**r**	**R^2**
ALL	0.147	0.022
1988	0.446	0.199
1989	0.537	0.288
1990	0.607	0.368
1991	-0.010	0.000
1992	0.169	0.029
1993	0.581	0.337
1994	0.438	0.192
1995	0.424	0.180
1996	0.406	0.165
1997	0.425	0.181
1998	0.635	0.403
1999	0.157	0.025
2000	0.276	0.076
2001	0.059	0.003
2002	-0.103	0.011
2003	0.865	0.749

The effect of flow on chloride values at both stations and can be further explained through Figure 5-1. This chart compares the average yearly flow at Clyo against the percentage of samples taken by the City at the intake that exceed the assumed chloride benchmark of 12 mg/L, for each year. From the figure, it can immediately be realized that a strong relationship exists between lower flows and higher chloride values exceeding the benchmark. In particular, this is visible in 1988, 1989, 2000, 2001, and 2002.

Further, we might also derive a potential response in chloride values from this chart due to Savannah Harbor deepening, which took place in 1994. Annual average flows between 1990 and 1992, and then between 1995 and 1997 seem relatively consistent, varying approximately between 350 and 400 cms (12,360 and 14,125 cfs). However, the percentage of chloride samples exceeding 12 mg/L for either of these periods does not display the same level of similarity. Post-1994, and thus post-deepening, with relatively similar annual average flows, had more samples at the City's intake higher than the 12 mg/L benchmark than prior to deepening activities. This strongly suggests that harbor deepening may prompt elevated salinity by allowing more saltwater intrusion upstream, therefore inducing higher chloride values at the City's intake.

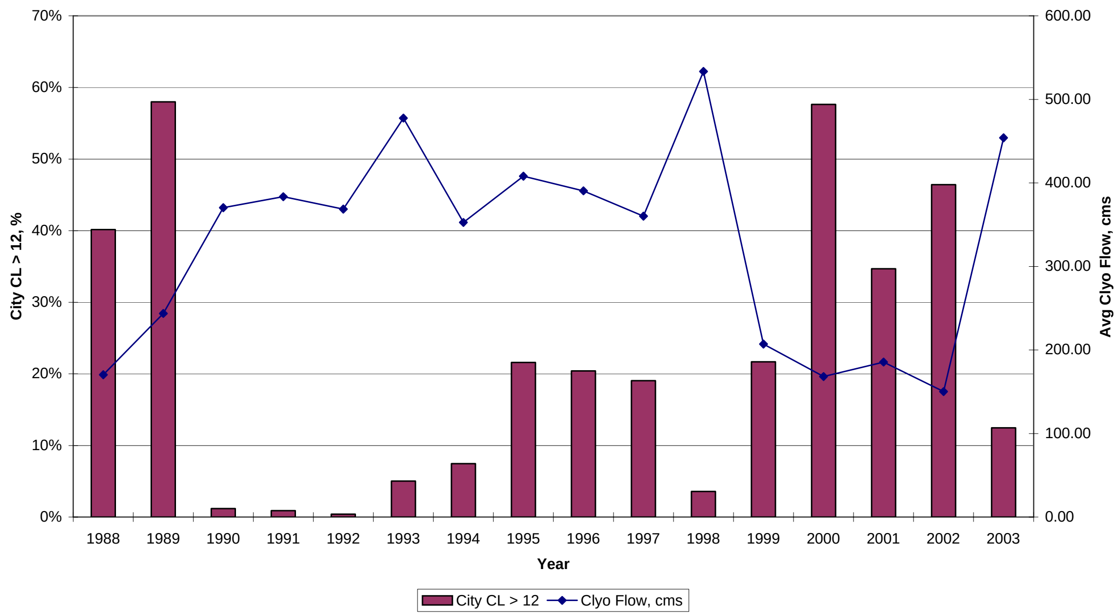

Figure 5-1 Annual Average Flow against Percentage of Samples Greater than 12 mg/L

A closer look can also be taken at monthly flows for those years with similar annual average flows; between 1990 and 1992 and between 1995 and 1997, and the exceedances of the benchmark for chlorides for each month. Table 5-3 provides a summary of this data for each year within these periods.

Table 5-3 Monthly Flow and Chloride data for Periods of Similar Annual Average Flows

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1990	**Average Flow**	419	555	944	400	318	239	191	225	223	406	266	230
	# CL Samples	21	19	22	21	22	21	22	23	19	22	20	18
	%>12 mg/L	9.5	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6
1991	**Average Flow**	301	409	529	467	590	356	376	656	306	193	239	224
	# CL Samples	21	19	21	22	22	20	16	10	19	14	19	21
	%>12 mg/L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	0.0	14.3
1992	**Average Flow**	292	278	392	358	189	296	256	288	258	421	368	1012
	# CL Samples	21	19	22	22	20	22	21	21	21	22	18	21
	%>12 mg/L	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0
Harbor Deepening													
1995	**Average Flow**	534	593	845	283	203	245	216	295	342	324	495	524
	# CL Samples	20	19	23	20	22	22	20	23	20	21	20	20
	%>12 mg/L	0.0	10.5	0.0	10.0	81.8	54.5	55.0	0.0	0.0	14.3	0.0	30.0
1996	**Average Flow**	295	703	718	506	294	315	230	246	233	207	---	---
	# CL Samples	21	20	21	22	22	20	21	23	19	2	---	---
	%>12 mg/L	33.3	0.0	0.0	9.1	22.7	0.0	38.1	39.1	42.1	0.0	---	---
1997	**Average Flow**	350	439	627	328	358	274	244	278	---	---	---	---
	# CL Samples	21	19	21	22	21	21	22	21	---	---	---	---
	%>12 mg/L	42.9	26.3	0.0	27.3	14.3	42.9	4.5	19.0	---	---	---	---

Table 5-3 further confirms that increases in exceedances of the 12 mg/L chloride benchmark post-deepening were observed throughout the year at the City's intake, possibly due to increased saltwater intrusion. It is interesting to note though that post-deepening, dramatic increases in the percentage of exceedances of the benchmark are seen more clearly in the warmer months (May – August), which experience relatively low flows throughout each year. For example, data for 1995 shows exceedances between 55-82 percent for chloride samples taken from May through July. These months also experienced some of the lowest average flows of that year, between 203-245 cms. In 1993, pre-deepening, no exceedances were observed in these months. Table 5-4 presents the percent exceedances by year for the City's intake data along with a reference to meteorological, hydrological, and physical changes within the system.

Table 5-4 Percent Exceedances of City's Chloride Data by Year

Year	Count	Exceed 12?	Percentage	Circumstances
1988	250	99	40%	drought
1989	251	146	58%	drought
1990	251	3	1%	
1991	250	2	1%	
1992	251	1	0%	dredged Abercorn Creek
1993	252	15	6%	
1994	252	17	7%	Harbor deepening
1995	250	54	22%	
1996	191	39	20%	
1997	168	32	19%	
1998	251	9	4%	drought
1999	249	52	21%	drought
2000	328	180	55%	drought
2001	364	152	42%	drought
2002	365	172	47%	drought
2003	366	50	14%	
1988 - 2003	4289	1023	24%	

Based on the data analysis to this point, there is a definitive relationship between chloride values on Abercorn Creek and flow through the system. As demonstrated, the regressions provide high R^2 values for high flow years and a clear response is seen in the plots and tables provided. Table 5-4 also shows a relationship between low-flow years and high exceedances of chloride at the intake.

5.2 Flow and Chloride at Clyo in Relation to the Watershed

A supplemental analysis of flow and chloride data from the USGS station at Clyo (02198500) was conducted to better understand the relationship of these parameters throughout the Lower Savannah River watershed. There are a total of 28 chloride observations from this station between 1988 and 1994. By plotting these values directly against a flow time-series from the same station, as in Figure 5-2, an apparent power function between the two can be observed. A best-fit line of this nature may be plotted through the points yielding an R^2 of 0.759, indicating quite a strong relationship between flow and chlorides at this station. A plot of the data and the relationship between the two parameters is provided in Figure 5-3. The power function is represented by the following equation;

$$\mathbf{Chloride_{Flow} = 92.118 * Flow^{(-0.436)}}$$

Figure 5-2 Flow and Chloride Observations at Clyo, GA (USGS 02198500)

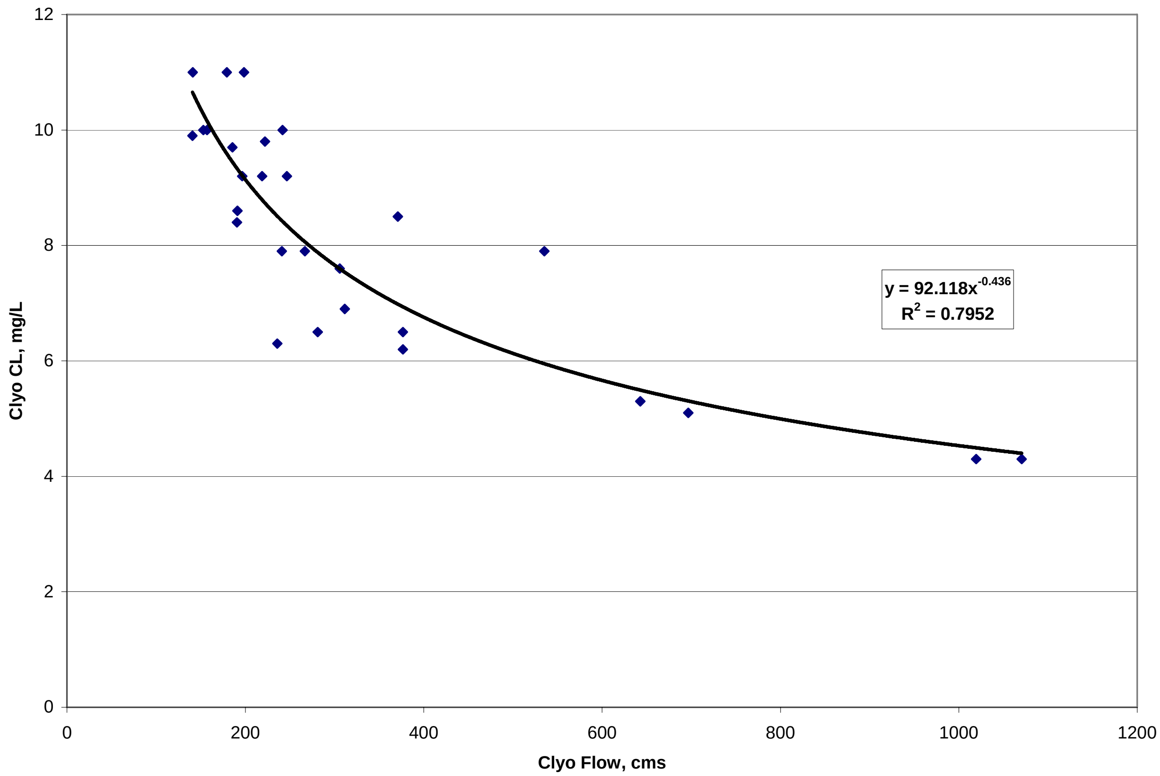

Figure 5-3 Correlation of Flow and Chloride Measurements at Clyo, GA (USGS 02198500)

The power function identified here was then used to plot a chloride time series at Clyo, and to provide a comparison in terms of trend against chloride values at Abercorn Creek intake, and those derived from specific conductance values at the I-95 Bridge. Figures 5-4 through 5-8 display the calculated chloride time series at Clyo. The calculated time series closely resembles the trend observed in measured chloride values at the Abercorn Creek intake, though it does seem to under-predict at times of relatively high flows. The time series is unable to capture chloride spikes at the intake during periods of low flow, or capture violations in the benchmark there. This indicates the possibility of additional chloride sources impacting the samples during a low flow period, thus making a statistical relationship on Clyo flows alone insufficient.

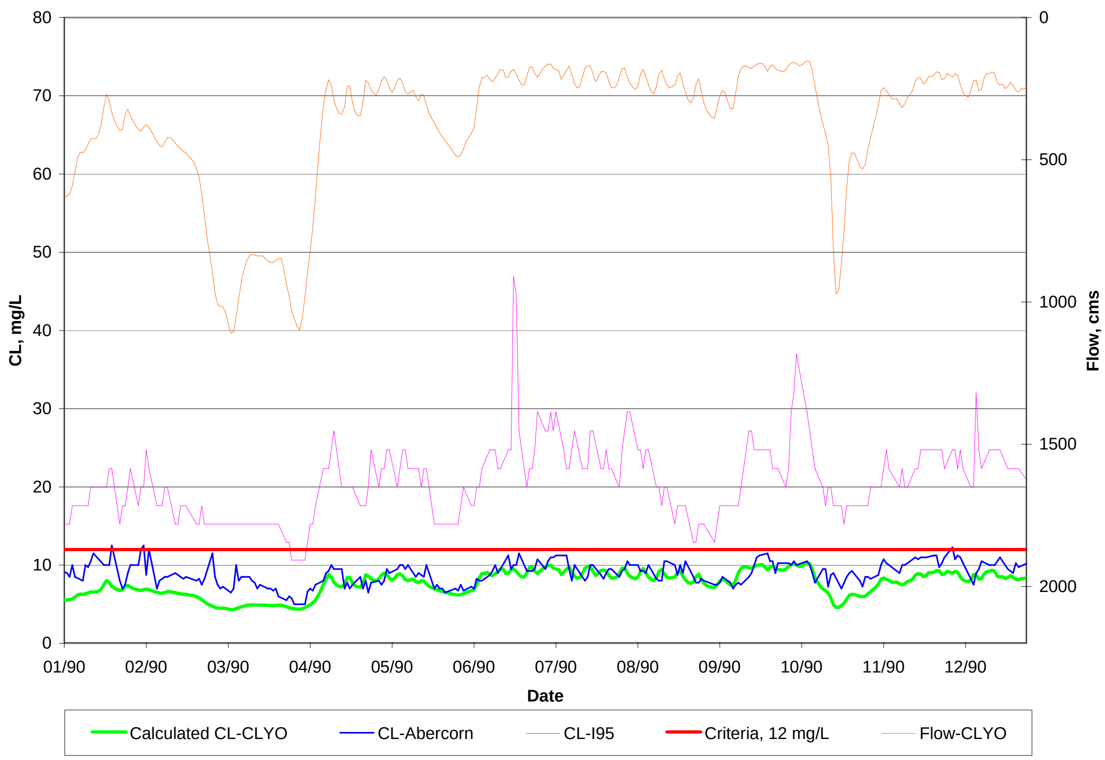

Figure 5-4 Calculated Chloride Time Series at Clyo - 1990

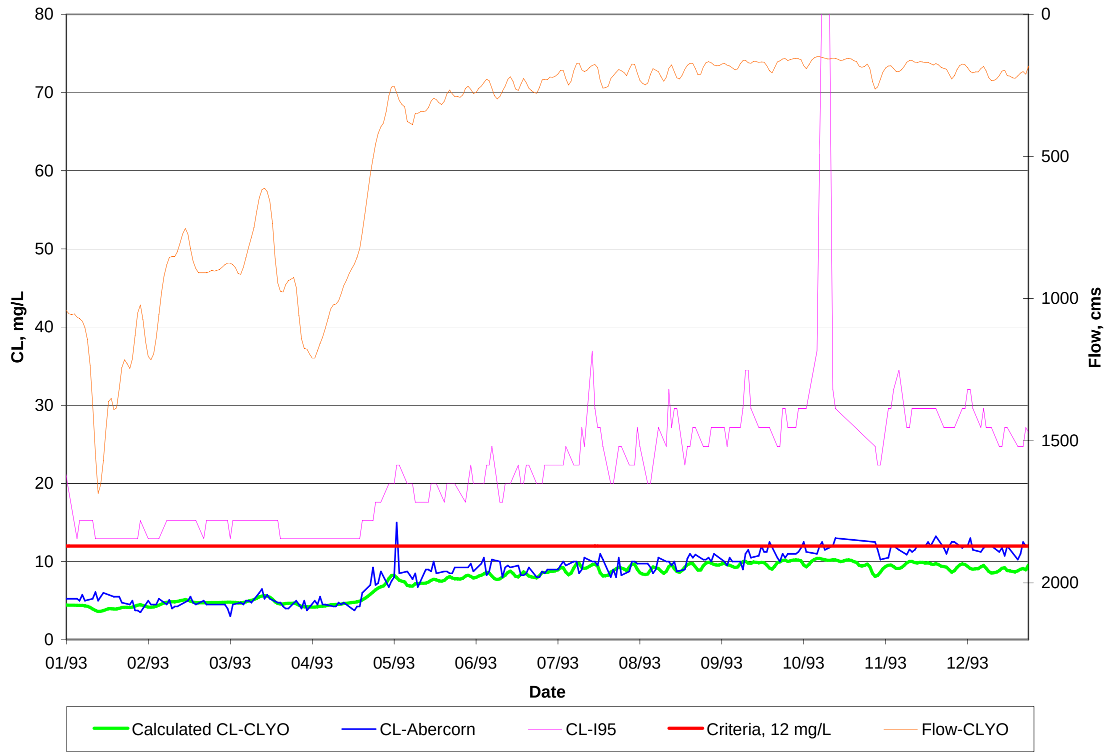

Figure 5-5 Calculated Chloride Time Series at Clyo - 1993

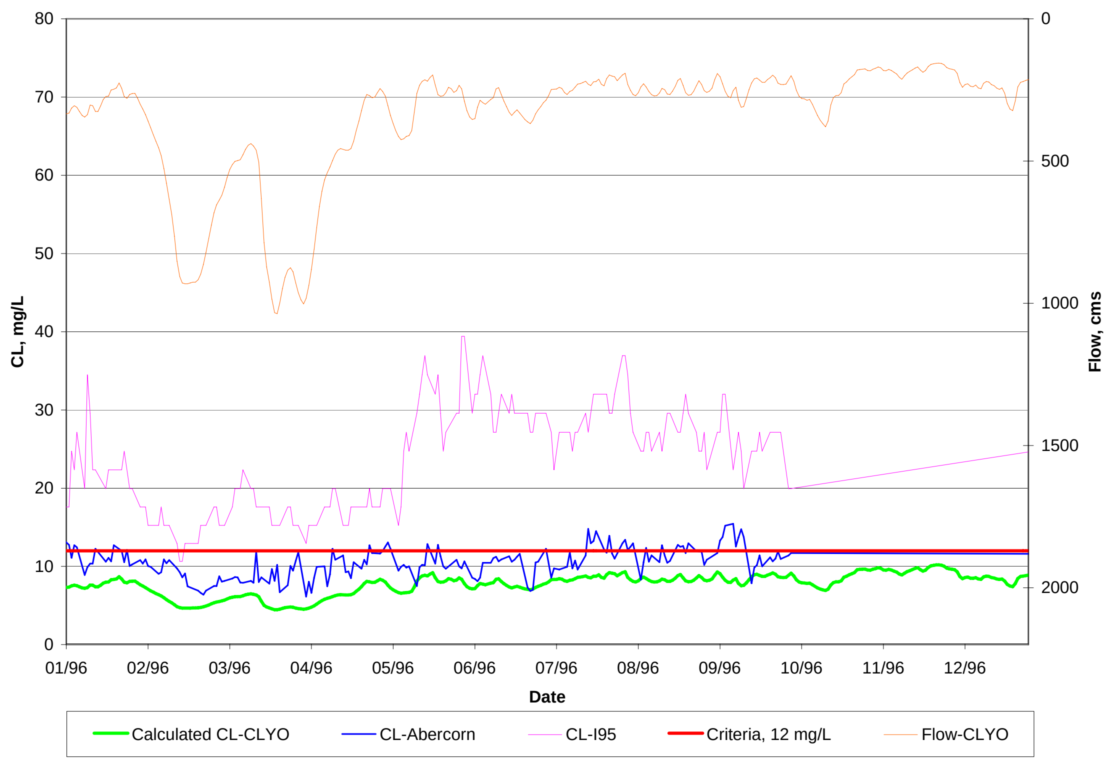

Figure 5-6 Calculated Chloride Time Series at Clyo - 1996

Figure 5-7 Calculated Chloride Time Series at Clyo - 2000

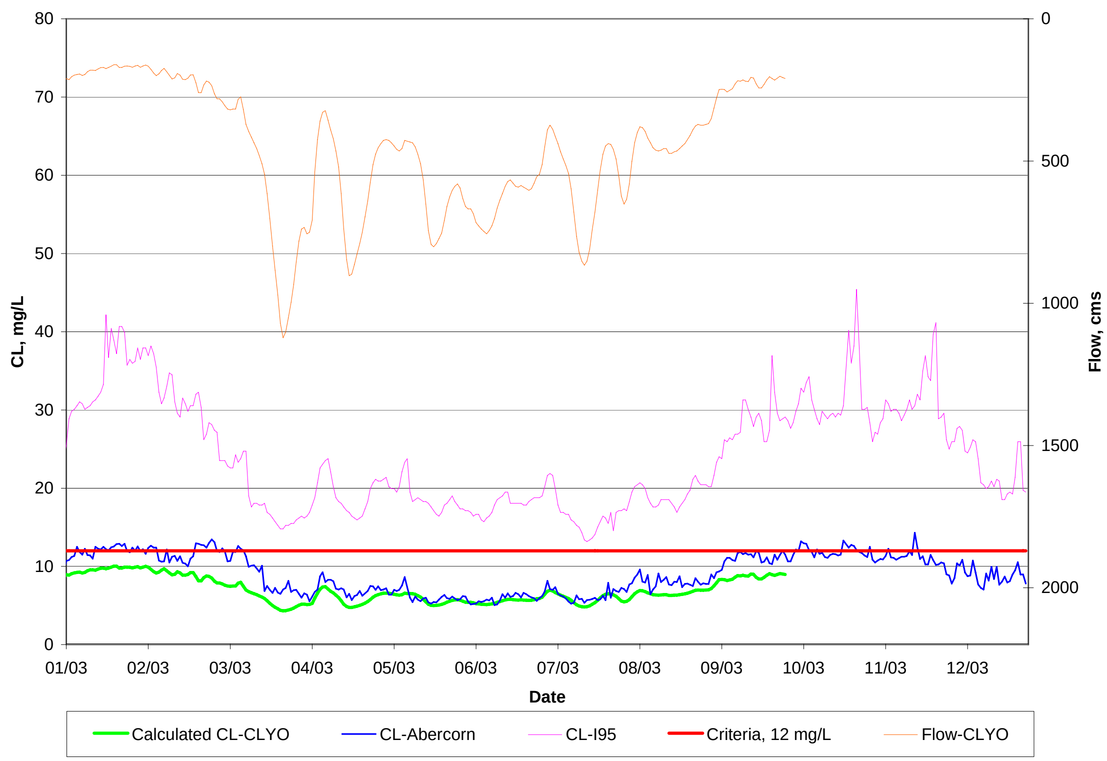

Figure 5-8 Calculated Chloride Time Series at Clyo - 2003

5.3 Supplemental Analysis with Water Quality Data Observed at the Intake

In addition to the data presented previously, the City of Savannah also measured specific conductance at the intake. Approximately 2200 corresponding records of conductance and chloride were taken by the City at the intake from 1997 through 2006. These data are provided in Figure 5-9 where the similarities in trend of the two data sets may be observed. The trend is visible in both constituents between 1998 and 2001, where a gradual increase in concentrations is seen. Then in 2001, 2003 and the end of 2004 significant reductions in concentrations are correspondingly observed in both specific conductance and chlorides.

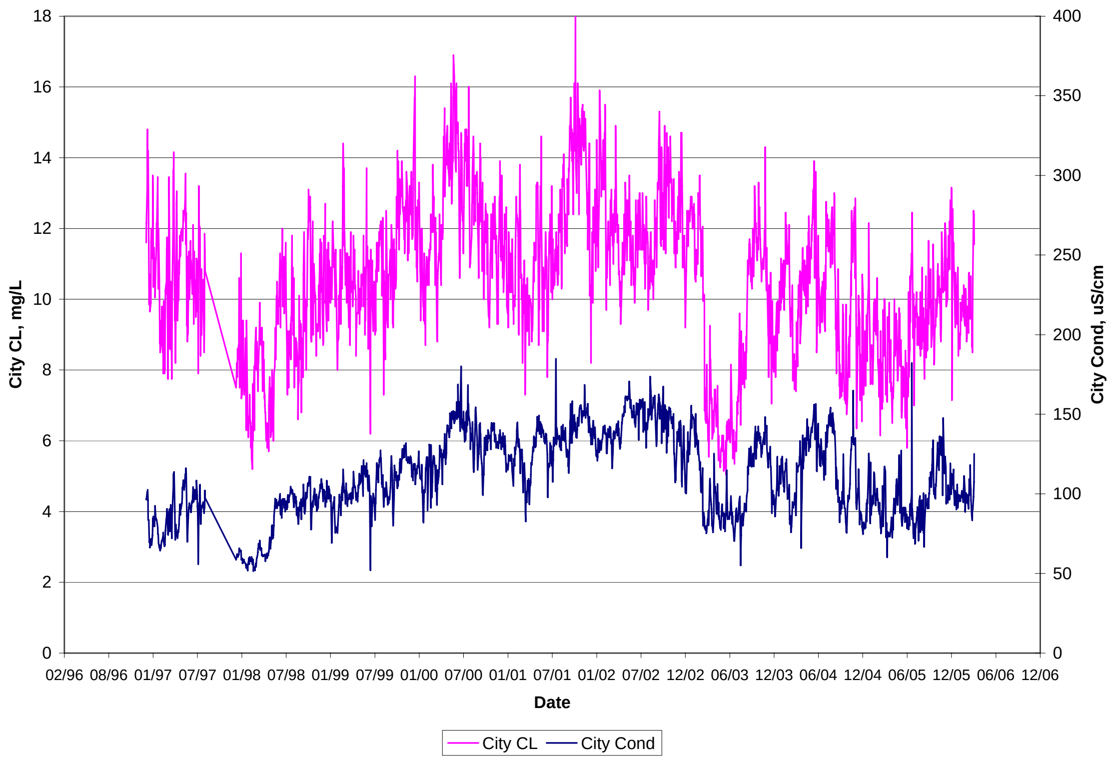

Figure 5-9 Specific Conductance versus Chloride at the City's Intake

It is assumed here that the relationship between specific conductance and chlorides observed at the intake may be used to represent the salinity influences from the harbor. By conducting a regression analysis on these constituents, a linear relationship between specific conductance and chloride concentrations at the intake may be identified. The results of this regression are shown in Figure 5-10. The regression resulted in an R-squared value of 0.49 and at a 95% confidence interval, the sample set had an error of ±0.41 mg/L. The relationship between the specific conductance and chloride concentrations at the intake based on this regression may then be represented by the following equation;

$$\mathbf{Chloride_{Salinity} = 0.0574*(Conductance) + 4.1603}$$

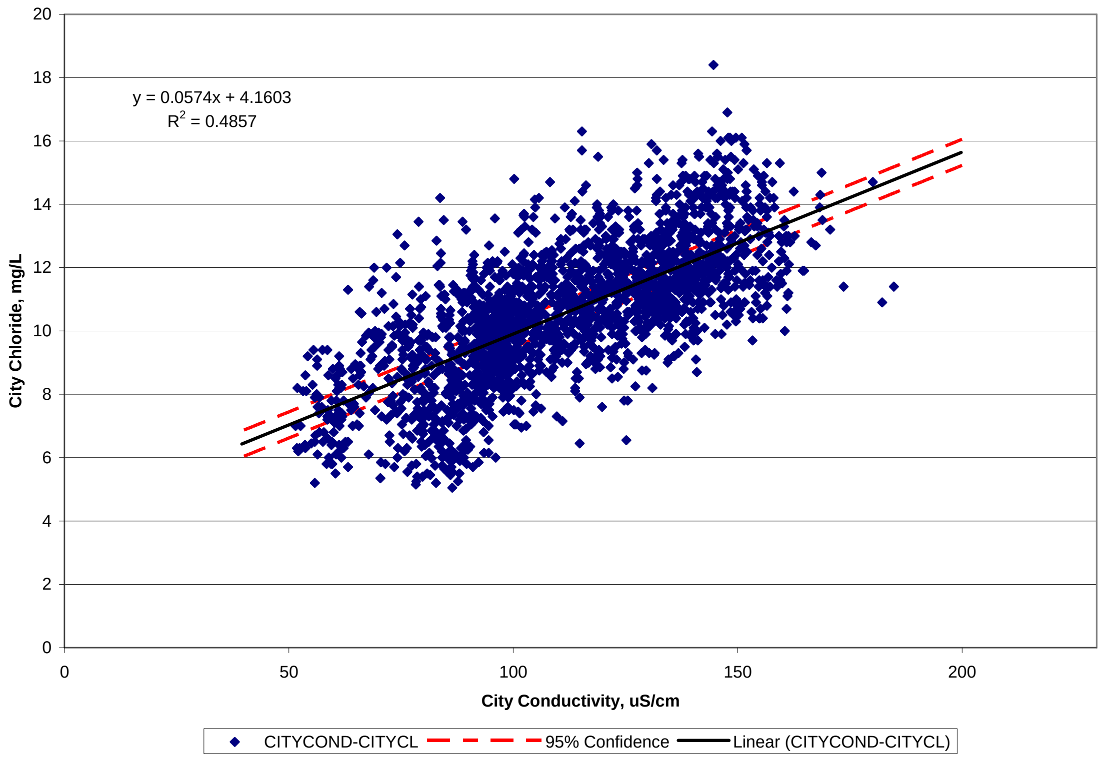

Figure 5-10 Regression of Specific Conductance versus Chloride at the City's Intake

6.0 Source Assessment

6.1 Upstream Sources

To identify whether upstream sources were contributing to chloride values in exceedance of the 12 mg/L benchmark in Abercorn Creek, all USGS stations located within and upstream of the Lower Savannah River watershed were queried and summarized. Table 6-1 and Figure 6-1 provide descriptive and locational information for each of these stations.

Chloride data from these stations were statistically examined to provide the temporal and numerical range and mean of chloride values at each station (Table 6-2). Chloride data were not available at two critical locations, 02198500 (Clyo) and 02198840 (I-95 Bridge). Though limited in sample size, the data indicates that there is a baseline value for chlorides from upstream sources, with an overall mean of 2.31 mg/L and an overall maximum of 6.5 mg/L from these stations, excluding 02198920 (Houlihan Bridge) and 02198980 (Fort Pulaski). There are no exceedances of the chloride benchmark in these samples. Though these observations are deemed additive to chloride values in the Lower Savannah River watershed, they do not suggest that upstream sources are a specific contributor to violations in chloride at the Abercorn Creek intake.

Table 6-1 USGS Stations Within and Upstream of the Lower Savannah River Watershed

Agency	Station	Station Description	Lat	Long
USGS	02187500	SAVANNAH RIVER NEAR IVA, S.C.	34.2556	82.7450
USGS	02189000	SAVANNAH RIVER NEAR CALHOUN FALLS, S. C.	34.0700	82.6417
USGS	02192500	LITTLE RIVER NEAR MT. CARMEL, SC	34.0692	82.5014
USGS	02196000	STEVENS CREEK NEAR MODOC, SC	33.7292	82.1853
USGS	02196838	BUTLER CREEK RESERVOIR AT FORT GORDON, GA	33.5150	82.0022
USGS	02197300	UPPER THREE RUNS NEAR NEW ELLENTON, SC	33.3839	81.6133
USGS	02198500	SAVANNAH RIVER NEAR CLYO, GA	32.5281	81.2689
USGS	02198840	SAVANNAH RIVER NEAR PORT WENTWORTH, GA	32.2356	81.1514
USGS	02198920	SAVANNAH RIVER AT GA 25 AT PORT WENTWORTH, GA	32.1658	81.1539
USGS	02198980	SAVANNAH RIVER AT FORT PULASKI, GA	32.0339	80.9033

Table 6-2 Summary of Chloride Observations from USGS Stations Upstream of the Lower Savannah River Watershed

	02187500	02189000	02192500	02196000	02196838	02197300	02198920*	02198980*
# Observations	34	21	2	1	1	150	33	209
First Year	1957	1956	1959	1961	1999	1967	1958	1960
Last Year	1972	1972	1961	1961	1999	1993	2003	1960
Minimum CL, mg/L	1.4	1.2	2	6.5	3.68	0.2	3.2	3.8
Maximum CL, mg/L	4.7	4.4	2	6.5	3.68	3.7	6,900	11,000
Mean CL, mg/L	2.44	2.54	2.00	6.50	3.68	2.22	2,239	4,848

* stations are located in the estuary where salinity is frequently present.

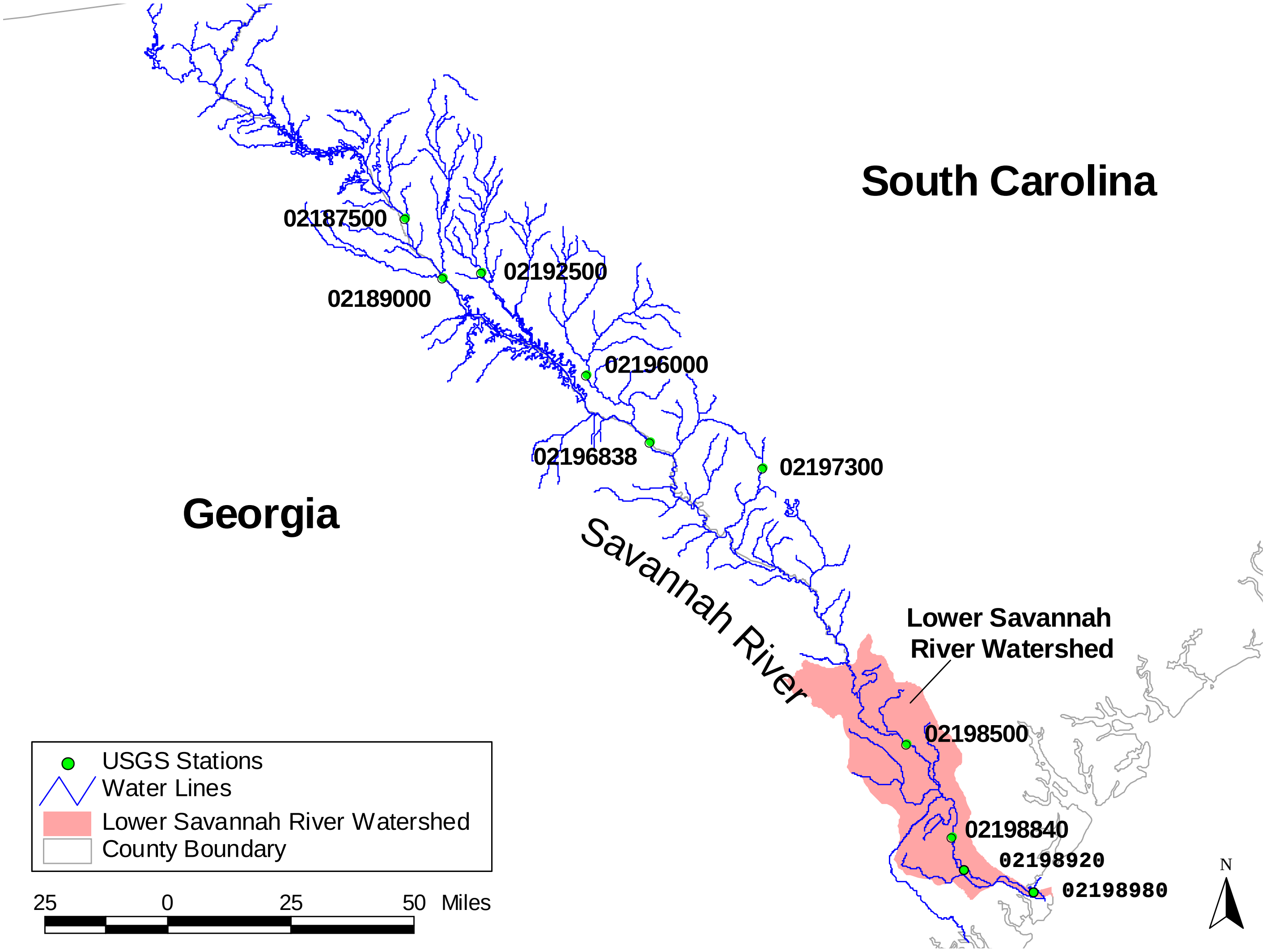

Figure 6-1 USGS Station Locations Within and Upstream of the Lower Savannah River Watershed

6.2 Point Sources

There are few industrial facilities upstream of the Abercorn Creek intake that contain chlorine in their effluent. For these facilities, any limitations or monitoring for salts such as chlorides would only be considered if there were water quality concerns, which is not the case for any current point source discharge to the Savannah River. The Fort Howard (now Georgia Pacific) discharge near Rincon would have a dilution ratio of 200-300:1 based on 7Q10 flow.

GAEPD routinely assigns total residual chlorine limits to permitted municipal discharges. The effluent permit limits can range from 0.011 mg/L (for discharges to streams with very low 7Q10 streamflows) to 0.5 mg/L, which is the maximum allowed by their guidelines, and well below 12 mg/L at the intake.

6.3 Groundwater

This assessment anticipated groundwater to be a contributing source for chlorides in Abercorn Creek. The possible presence of a local spring, or elevated groundwater-surface water interactions, in the watershed due to coastal proximity and/or prominent wetlands within the area were suspected as potential factors. The absence of a contributory spring in the area was confirmed though upon referring to detailed topographic maps of the watershed and conducting a series of discussions with the groundwater counterparts to this study.

To address groundwater-surface water interactions, a USGS study published in 1997 was referenced. The study involved twelve wells in Chatham County that were pumped and sampled to determine groundwater conditions in Georgia. Figure 6-2 shows the locations of six of these wells within the Savannah River area. One of these wells, 37Q185, is located approximately 14 miles downstream of the Abercorn Creek intake. This well was tapped at an interval of 274-360 ft below the surface and data from it is given in Figure 6-3, measured from 1985 through 1997. (Cressler, 1997) The values obtained indicated that chloride concentrations within the aquifer do not change appreciably with time and generally fluctuate around 6 mg/L, well below 12 mg/L at the intake. This suggests that a baseline chloride signal does exist in the groundwater and it may have some impact on chloride values in surface water, but it is probably not the sole cause of exceedances of the benchmark.

Figure 6-2 Savannah River Wells Monitored by USGS

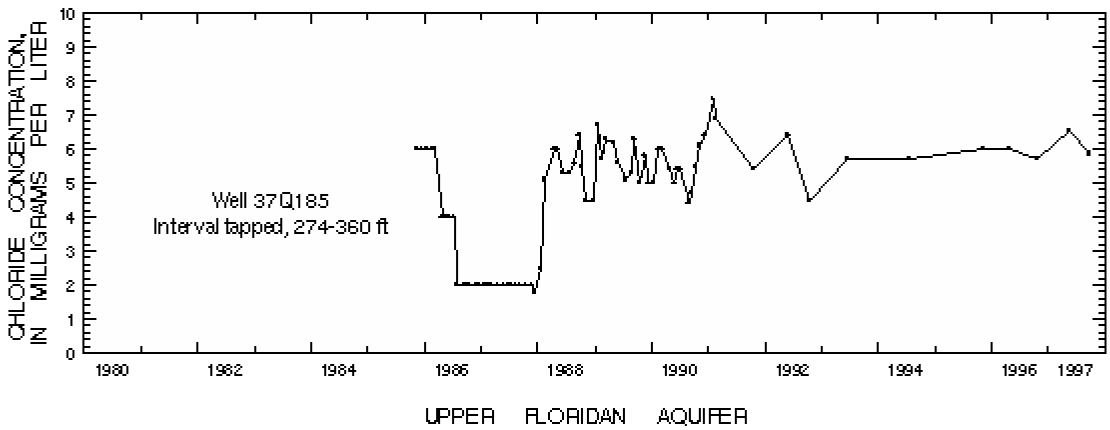

Figure 6-3 Data from USGS Well 37Q185

7.0 Development of Chloride Model

The chloride model (or prediction equation) based on flow alone was further assessed to provide more reliability in its overall function and result. It was necessary to establish a method by which all available data and a variety of analytical methods may be employed to ensure the best possible arrangement for predicting chloride. Based on the data analysis and source assessment, the chloride model will consist of two components; chlorides derived from upstream flow and those due to salinity from the harbor. The chloride model is represented as the following:

$$\mathbf{Chloride_{Intake} = Chloride_{Flow} + Chloride_{Salinity}}$$

A prior analysis had defined a direct relationship for the first component of this equation, where chloride concentrations at the USGS gage at Clyo (02198500) were written as a function of the upstream flow measured there.

$$\mathbf{Chloride_{Flow} = 92.118 * Flow^{(-0.436)}}$$

To define the second (salinity) component of the predictive equation, a 7-year, hourly time-series of salinity was obtained from the calibrated EFDC model for Savannah Harbor. The salinity time series was extracted from the middle layer of model grid cell (8,130) at the intake location and was converted by a two-step process to provide a simulated chloride time-series. This conversion may be represented by the following equation:

$$\mathbf{Salinity_{EFDC} \rightarrow Cond_{USGS} \rightarrow Chloride_{Salinity}}$$

The first step of the conversion required the application of published algorithms provided by USGS on the salinity record and resulted in a time-series of conductivity ($COND_{USGS}$) at the intake (Miller, 1988). The second step of the conversion took into account the relationship between conductivity and chloride concentrations. This relationship was developed using a regression analysis conducted on observed data for these constituents, taken at the City of Savannah's intake on Abercorn Creek. By applying this relationship, a 7-year time-series of the salinity influenced chloride concentrations at the intake was obtained. Figure 5-10 provides a graphical representation of this regression and the following equation defines the relationship between conductivity and chlorides based on this analysis:

$$\mathbf{Chloride_{Salinity} = 0.0574 * (Salinity_{EFDC} \rightarrow Cond_{USGS}) + 4.1603}$$

The resulting relationship to predict chloride concentrations at the City's intake can then be written as follows:

$$\mathbf{Chloride_{Intake} = Chloride_{Flow} + Chloride_{Salinity}}$$

$$\mathbf{Chloride_{Intake} = [92.118 * Flow^{(-0.436)}] + [0.0574 * (Salinity_{EFDC} \rightarrow Cond_{USGS}) + 4.1603]}$$

This relationship can be plotted as a time-series and is represented in Figures 7-1 and 7-2. These have been split into two separate time periods to meet data record limitations in the application and provide ease of interpretation. The predictive equation provides a relatively accurate depiction of the trend of chloride values observed at the intake (INTAKE-CL), though it does tend to overpredict some of the observations.

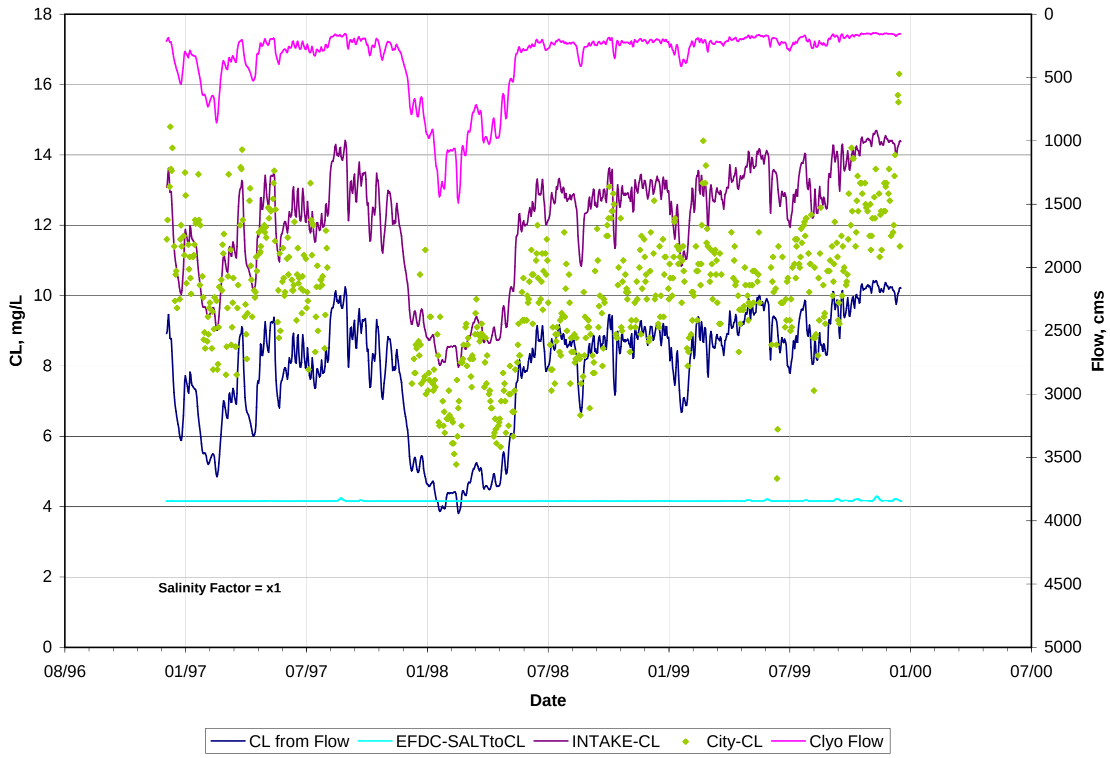

Figure 7-1 Predicted Chlorides at the Intake (1997 through 1999)

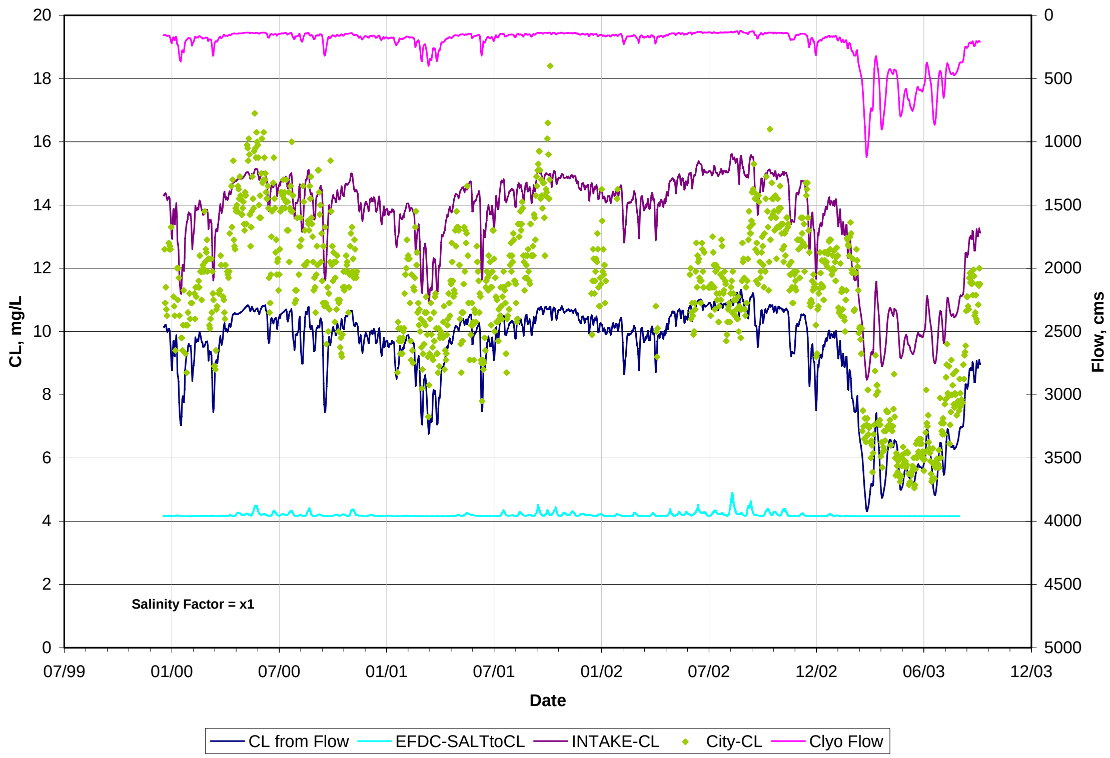

Figure 7-2 Predicted Chlorides at the Intake (2000 through 2003)

By conducting a regression analysis between the chloride values predicted by the model and the chloride measurements observed at the City's intake, a linear relationship may be identified. The results of this regression are shown in Figure 7-3. The regression resulted in an R-squared value of 0.59. The accuracy of the model can be further interpreted through a 95% confidence interval which results in a range of ±0.33 mg/L, shown in Figure 7-3.

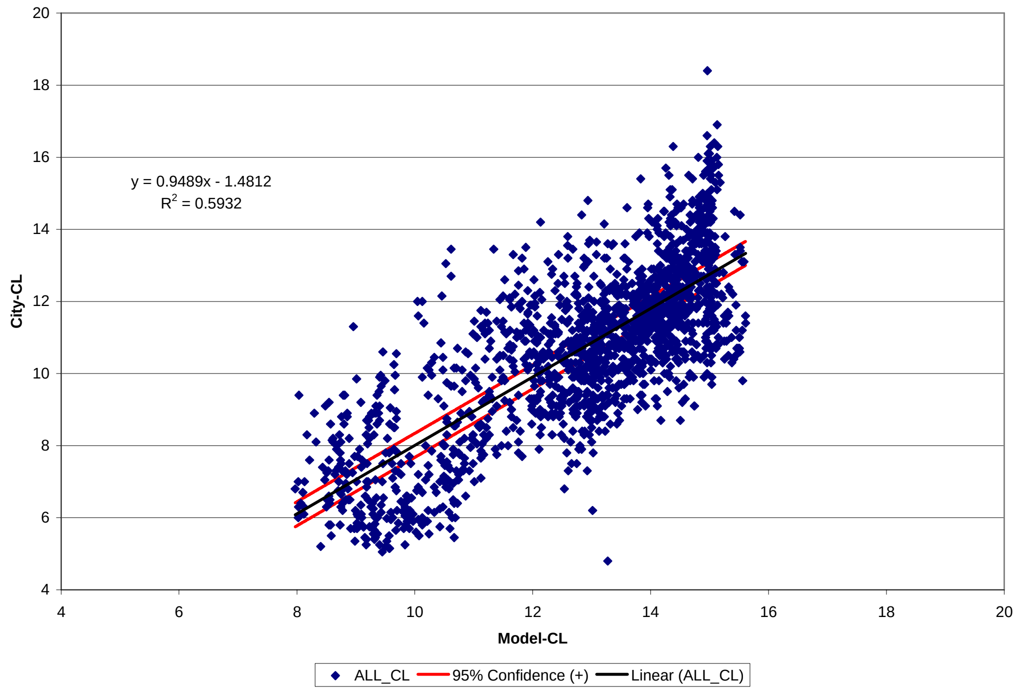

Figure 7-3 Relationship between the City's Measurements of Specific Conductivity and Chloride

Table 7-1 further provides a host of descriptive statistics for chloride measured at the intake and the output from the Chloride Model for the period of 1997 through 2003. These aid in defining the accuracy of the prediction, as well as the range of the model error.

Table 7-1 Descriptive Statistics for the Observed Chloride and Output from the Chloride Model

Statistics	CL - Observed	CL - Model
Range, mg/L	13.600	7.641
Maximum, mg/L	18.400	15.611
Mean, mg/L	10.733	12.872
Standard Deviation	2.324	1.887
Sample Variance	5.402	3.559
Standard Error (Root Mean)	0.056	0.046
R^2	0.593	
Average % Model Error	11.12	

Figure 7-4 presents a cumulative frequency distribution of the City's chloride measurements versus the chloride model results.

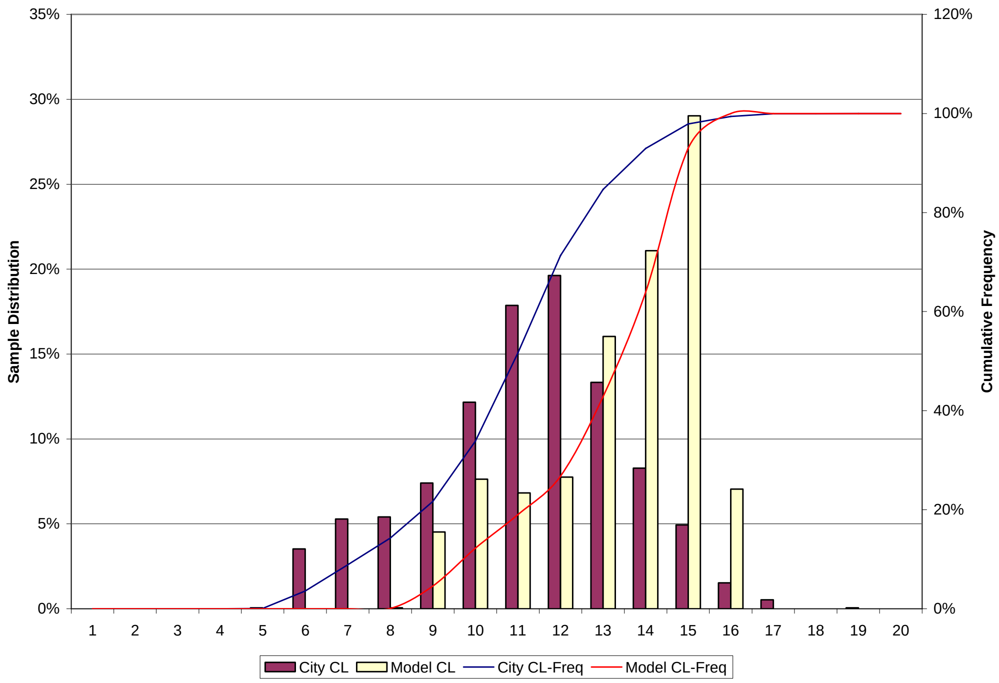

Figure 7-4 Cumulative Chloride Distribution of the City and Model Results

To further assess the Chloride Model, the predicted chlorides and the City's observations were both compared annually against various chloride concentration benchmarks (X). The concentrations used in this comparison were 8mg/L, 10 mg/L, 12 mg/L, 14 mg/L, 16 mg/L and 18 mg/L. The comparison also calculated the annual average difference by which the model results and the City's observations were higher than the benchmark. The comparison is summarized in Table 7-2.

The summary indicates that the model is able to relatively accurately mimic the number of samples that are in exceedance of the benchmark at 8 and 10 mg/L, as compared to the City's measurements. As the benchmark concentration is increased to 12 mg/L, the model is found to be over-predicting more than the City observations, though only by an average difference of about 1.4 mg/L. As the benchmark concentration is increased to 14 mg/L, the model over-predicts by an even smaller average difference, and then never gets higher than 16 mg/L. The City's observations do show occasional exceedances beyond 14 mg/L, but these are few in number and only represent average differences of between 0.3 and 1.0 mg/L. There is only one sample taken by the City that is greater than 18 mg/L indicating the infrequency of such events.

Table 7-2 Summary of Model Results and City Observations with Respect to Various Benchmarks for Chloride Concentration (X)

X - Chlorides mg/L	Year	Total Obs.	Model > X # Samples	Model > X % Samples	Model > X Avg. Difference	City > X # Samples	City > X % Samples	City > X Avg. Difference
8	1997	168	168	100.0	3.56	163	97.0	2.83
8	1998	252	251	99.6	3.12	169	67.1	1.73
8	1999	226	226	100.0	5.31	222	98.2	3.04
8	2000	288	288	100.0	6.18	288	100.0	4.56
8	2001	271	271	100.0	5.83	269	99.3	3.47
8	2002	224	224	100.0	6.69	224	100.0	4.12
8	2003	273	273	100.0	3.12	124	45.4	3.00
7 Year Summary		**1702**	**1701**	**99.9**	**4.87**	**1459**	**85.7**	**3.41**
10	1997	168	148	88.1	1.84	116	69.0	1.48
10	1998	252	152	60.3	2.61	59	23.4	1.14
10	1999	226	226	100.0	3.31	164	72.6	1.62
10	2000	288	288	100.0	4.18	270	93.8	2.77
10	2001	271	271	100.0	3.83	208	76.8	2.09
10	2002	224	224	100.0	4.69	214	95.5	2.23
10	2003	273	185	67.8	1.93	95	34.8	1.67
7 Year Summary		**1702**	**1494**	**87.8**	**3.39**	**1126**	**66.2**	**2.06**
12	1997	168	69	41.1	0.65	32	19.0	0.93
12	1998	252	133	52.8	0.83	9	3.6	0.52
12	1999	226	208	92.0	1.46	49	21.7	1.07
12	2000	288	277	96.2	2.28	166	57.6	1.74
12	2001	271	249	91.9	2.04	94	34.7	1.39
12	2002	224	222	99.1	2.71	104	46.4	1.29
12	2003	273	88	32.2	1.24	34	12.5	0.54
7 Year Summary		**1702**	**1246**	**73.2**	**1.85**	**488**	**28.7**	**1.35**
14	1997	168	0	0.0	0.00	3	1.8	0.38
14	1998	252	0	0.0	0.00	0	0.0	0.00
14	1999	226	62	27.4	0.30	5	2.2	1.22
14	2000	288	196	68.1	0.61	65	22.6	0.91
14	2001	271	151	55.7	0.50	24	8.9	1.04
14	2002	224	192	85.7	0.93	23	10.3	0.53
14	2003	273	13	4.8	0.12	0	0.0	0.00
7 Year Summary		**1702**	**614**	**36.1**	**0.64**	**120**	**7.1**	**0.87**
16	1997	168	0	0.0	0.00	0	0.0	0.00
16	1998	252	0	0.0	0.00	0	0.0	0.00
16	1999	226	0	0.0	0.00	1	0.4	0.30
16	2000	288	0	0.0	0.00	5	1.7	0.34
16	2001	271	0	0.0	0.00	3	1.1	1.03
16	2002	224	0	0.0	0.00	1	0.4	0.40
16	2003	273	0	0.0	0.00	0	0.0	0.00
7 Year Summary		**1702**	**0**	**0**	**0**	**10**	**0.6**	**0.55**
18	1997	168	0	0.0	0.00	0	0.0	0.00
18	1998	252	0	0.0	0.00	0	0.0	0.00
18	1999	226	0	0.0	0.00	0	0.0	0.00
18	2000	288	0	0.0	0.00	0	0.0	0.00
18	2001	271	0	0.0	0.00	1	0.4	0.40
18	2002	224	0	0.0	0.00	0	0.0	0.00
18	2003	273	0	0.0	0.00	0	0.0	0.00
7 Year Summary		**1702**	**0**	**0**	**0**	**1**	**0.1**	**0.40**

The annual average difference from each benchmark for the model predictions and the City's observations can also be illustrated, as in Figure 7-5. This provides a relative comparison between the two and indicates the over-prediction by the model between the 8mg/L to 12 mg/L benchmarks. The model displays an average difference relatively similar to the City's observations at the 14 mg/L benchmark. The Chloride Model never predicts values larger than the 16mg/L benchmark.

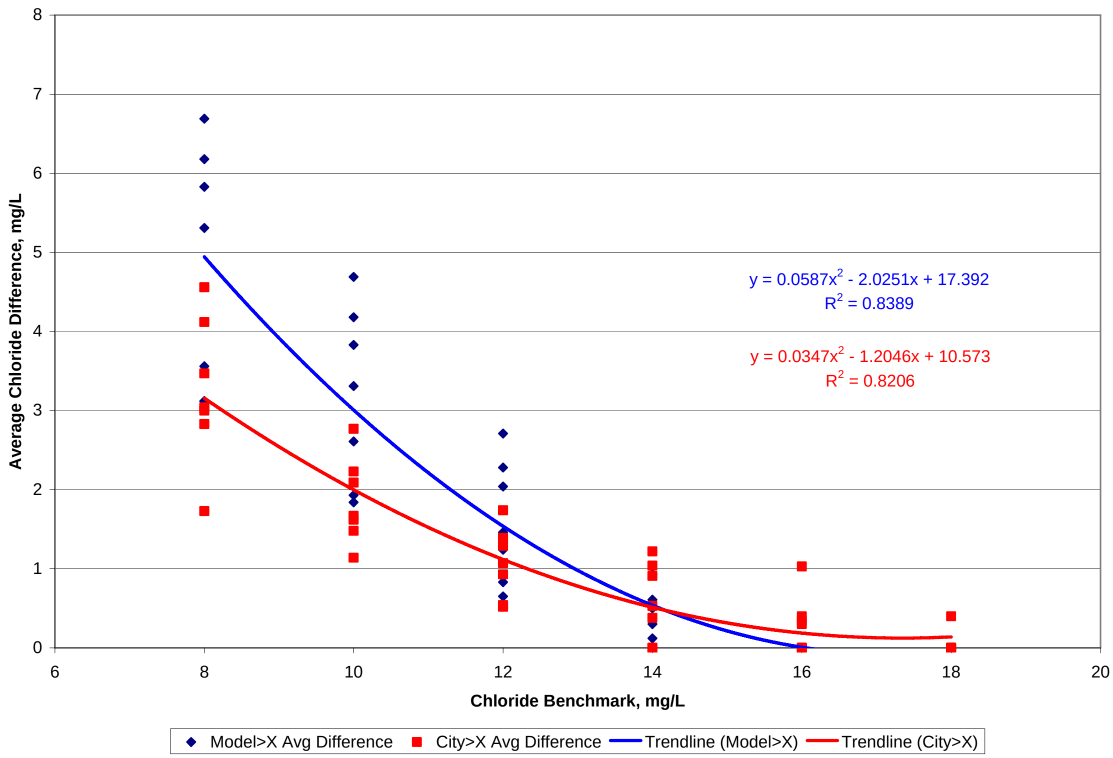

Figure 7-5 Average Difference between Model and City Values and the Chloride Benchmark

A summary of the City's chloride observations relative to the model's predictions are also provided in Table 7-3. This table illustrates the magnitude of the difference between the model's predictions and the City's observations. Of note is the largest range in chloride measurements made by the City (10.0 mg/L), which is observed when the model predicts at 13 mg/L.

Table 7-3 Summary of the City's Observations Relative to Predictions by the Chloride Model.

Model Prediction	City CL Observations at Intake, mg/L				
CL, mg/L	Average	Min	Max	Range	+/-
8	7.2	5.2	9.4	4.2	2.1
9	7.3	5.1	11.3	6.3	3.1
10	7.4	5.2	12.1	7.0	3.5
11	8.9	5.5	13.4	8.0	4.0
12	10.4	7.7	14.2	6.5	3.3
13	10.6	4.8	14.8	10.0	5.0
14	11.8	8.7	16.3	7.6	3.8
15	12.8	8.7	18.4	9.7	4.8

8.0 Conclusions

This study attempted to better understand chloride levels at the City of Savannah's freshwater intake on Abercorn Creek. It successfully met all of its anticipated objectives by providing a summary of the available data, determining the relationship between upstream flow and chloride measurements within the system, investigating the impact of past harbor deepening on chloride levels at the intake, addressing other potential sources of chlorides, and developing a predictive model for chloride concentrations.

It was immediately clear that the data available for this study were limited. The lack of flow and hourly chloride values at the City's intake required the analysis to rely on data from other locations within the watershed and to make assumptions on conditions at the intake itself. However, the analysis solidified the presumption that chloride levels at the Abercorn Creek intake are inversely related to flow in the Savannah River, as is the case throughout the system. Further, the study strengthens the suggestion that saltwater intrusion into the system plays a major factor for chloride concentrations at the intake. This is more pronounced during low flow periods. The lack of localized chloride data on Abercorn Creek limited the analysis from quantifying the magnitude by which chlorides at the intake vary due to changes in upstream flow and saltwater intrusion.

Upstream sources, point sources, and groundwater intrusion were not found to contain chloride concentrations that would directly cause exceedances of the benchmark. No point sources with relevant chloride permits were located nearby or upstream. Upstream sources displayed an overall average of 2.31 mg/L, while groundwater values fluctuated around 6 mg/L. It is likely that these sources have a cumulative impact on chloride values at the intake, but they are not responsible for samples found in exceedance of 12 mg/L.

Figure 5-2 proves that the upper Savannah River contains approximately 10 mg/L during low flows (highest of 11 mg/L) and 4 mg/L during extremely high flows (> 1,000 cms and 35,000 cfs). The lower ranges of chloride are diluted with higher inflows and watershed drainage in the basin. Therefore, it is during these critical low flow periods where the chloride is a 10 mg/L and salinity intrusion can cause an additional 2-3 mg/L to exceed 12 mg/L at the intake. The raised levels of chloride from the upper Savannah River in addition to the salinity intrusion causes the chloride on Abercorn Creek to be higher than 12 mg/L at times.

These results will be used in the future to determine impacts on chloride concentrations at the City's Intake. Based on the chloride model presented in this report, it will be included in the SHE Model Post-Processor to determine chloride concentrations on Abercorn Creek and determine how they respond to projected uses of the harbor. This chloride model presented herein will use the simulated salinity from the Enhanced Grid of the Environmental Fluid Dynamics Code (EFDC) model at the Abercorn Creek along with freshwater flow inputs at the USGS Gage near Clyo, GA to estimate a change in chloride concentration at the intake.

As discussed in this report, the chloride concentrations on Abercorn Creek are a function of chloride due to upstream Savannah River sources and salinity from the harbor. Based on the analysis, the results of the Chloride Model are accurate to ±0.33 mg/L at a 95% confidence level. In summary, the following equation combines both sources of chloride and will be used to make predictions at the City's Intake:

$$\mathbf{Chloride_{Intake} = [92.118*Flow^{(-0.436)}] + [0.0574*(Salinity_{EFDC} \rightarrow Cond_{USGS}) + 4.1603]}$$

where: **Chloride$_{Intake}$** is in mg/L, **Flow** is in cms and measured at USGS Clyo Gage 02198500, **Salinity$_{EFDC}$** is in ppt and the salinity output from the EFDC model.

9.0 References

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